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Thermal Conductivity and Electrical Resistivity of Six Copper-Base Alloys

M. C. I. Siu, W. L. Carroll, and T. W. Watson

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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*
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Thermal Conductivity and Electrical Resistivity of Six Copper-Base Alloys*, +

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ABSTRACT

Measurements of the thermal conductivity, λ, and electrical resistivity, ρ, of oxygen free copper and six copper-base alloys in the temperature range 298 to 924 K are presented. Except for copper, the λ and ρ values of copper alloys having the same chemical composition as those given in this paper have not been previously reported. The measured values of λ ($W \cdot m^{-1} \cdot K^{-1}$) and ρ ($\Omega \cdot m$) were found to conform, within 10 percent, to the predictions of the Smith-Palmer equation, $\lambda = 2.39 \times 10^{-8} T/\rho + 7.50$ $[W \cdot m^{-1} \cdot K^{-1}]$, where T is the thermodynamic temperature expressed in kelvins.

Key Words: Copper-base alloy properties; electrical resistivity; Smith-Palmer equation; thermal conductivity

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1. Introduction

The thermal conductivity, λ, of copper and a large number of copper alloys have been previously measured [1]. In many instances, measurements were made at temperatures below 100 K.

It is known [2,3] that λ of a copper alloy usually can be predicted with sufficient accuracy for practical purposes from a measurement of its electrical resistivity, ρ. Specifically, measured values of λ and ρ of many copper alloys between 293 and 473 K were observed [2,3] to obey the Smith-Palmer equation, $\lambda = 2.39 \times 10^{-8}\ T/\rho + 7.50$ $[W \cdot m^{-1} \cdot K^{-1}]$, where T is the thermodynamic temperature expressed in kelvins, to within 10-15 percent. In the present investigation, it was desired to know the thermal conductivity of a number of specific copper alloys over a larger temperature range than that in which the Smith-Palmer equation is known to hold accurately.

Results of the measurements of λ and ρ of oxygen free copper and six copper-base alloys from 298 to 924 K are presented in this paper. Samples for measurement were provided by the National Aeronautics and Space Administration (NASA), Lewis Research Center, Cleveland, Ohio. Measured values were compared with those obtained from the Smith-Palmer equation. Except for oxygen free copper, λ and ρ values of copper alloys having the same chemical compositions as those found in this paper have not been previously reported.

2. Specimens and Apparatus

The copper-base metals provided by NASA for these measurements were in the form of either rectangular bars or right circular cylinders. Radiographs obtained from the exposure of these samples to the National Bureau of Standards cobalt-60 source (1.25 MeV gamma rays) showed that the samples did not contain observable voids. Results of laboratory determination of the chemical composition, thermal history and mechanical properties made on these copper alloys were supplied by NASA and are given in Tables 1a, 1b and 2.

Experimental data for calculating λ and ρ of the copper alloys were obtained using an apparatus which has been described in detail elsewhere by Watson and Robinson [4]. This apparatus employs an electric heater and a circulating water heat sink to maintain a steady-state longitudinal thermal gradient closely approximating one-dimensional heat flow in a rod-shaped specimen about 37 cm long and 0.64 cm in diameter. The specimen is mounted vertically and is coaxially surrounded by a stainless steel cylinder equipped with its own heater which is made to function as a thermal guard by adjusting its temperature profile to match, as closely as possible, that of the specimen, thereby reducing radial heat flows even further. A computerized analysis procedure is used to make final corrections to compensate for the small remaining amount of extraneous radial heat flow not eliminated by the apparatus. Alumina powder insulation surrounds both the specimen and the thermal guard.

Basically, λ was determined from measured input power to the specimen heater and the specimen temperature gradient, which was in turn determined using calibrated Pt /Pt -10%Rh thermocouples at seven known

positions spaced 3.5 cm apart along the specimen, creating six measurement intervals, or spans. Calculated values of λ were thus obtained at six different mean temperatures for each level of power input to the specimen heater (a "run").

While steady-state thermal conditions were being maintained for each run, electrical resistivity was measured by passing a measured direct current through leads attached to the ends of the specimen and measuring the voltage differences between adjacent platinum leads of the thermocouples along the specimen. Thermoelectric effects were accounted for by taking voltage measurements with current flowing in forward and reversed directions. All values of λ and ρ were computed using specimen dimensions determined at room temperature.

Vacuum and gas handling systems were added to the apparatus in order to make the particular measurements described in this paper in argon gas. This permitted higher temperatures than could be attained in air without encountering oxidation of the copper alloy specimens. All measurements were conducted with the specimen chamber backfilled with argon at a pressure of one atmosphere.

Typically, three runs were made with each specimen, starting at the lowest power input level to the specimen heater and increasing it for each subsequent run. The highest mean temperature of a span during the hottest run was about 925 K. After a complete set of measurements was made on specimen R2, it was completely removed and subsequently replaced in the apparatus. A second set of measurements was then obtained. Only two runs each were made for specimens R3 and R4, which limited the highest span mean temperatures to about 625 K in those cases. Specimens

were tested in the order: R2, R2 (repeat test), R9, R5, R14, R4 and R3. (For composition of the specimens, see Table 1.)

3. Results

Examination of the specimens after completion of measurements revealed that, except for oxygen free copper, R5, there was no significant amount of oxidation of the specimens. In the case of oxygen free copper, examination of the specimen after testing revealed that a crust about 0.01 cm thick and 7.6 cm long covered the hottest end of the specimen. This layer was observed to be detached from the specimen. Qualitative analysis made on a piece of crust material using an electron beam probe analyzer revealed the presence of an abundant amount of oxygen and copper. Thus, it is most likely that the crust formation was an oxide of copper. The maximum temperature range of the encrusted section of the specimen during the hottest run was about 775 K to 975 K, sufficiently high for the oxidation of copper. The change of cross-sectional area of the specimen as a result of oxidation was taken into account in the calculation of λ of R5.

Values of λ and ρ calculated from measured data are shown as individual points in Figures 1 and 2, respectively. R2 data is included from both sets of measurements made on the specimen. The curves shown in these figures represent cubic polynomials fitted to the individual specimen data points by the method of least squares, of the form $\lambda = \alpha_0 + \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3 (W \cdot m^{-1} \cdot K^{-1})$ and $\rho = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$ $(\Omega \cdot m)$. For T in degrees Celsius, values of the coefficients of these polynomials are given in Table 3. Numerical results, called "smoothed

values", calculated from the above equations at uniform temperature intervals, are presented in Tables 4 and 5.

Below 833 K values of λ for specimen R2 obtained in the repeated measurement were in agreement to within 0.5 percent to that of the initial run. Between 833 and 920 K, results of the two successive measurements were in agreement to within 1.5 percent. Values of λ for oxygen-free copper obtained in this work agree within better than 3 percent with the values recommended by Touloukian, et al [1] over the full temperature range of the results obtained in the present effort, except for the highest temperature point (about 925 K, Fig. 1). This point is anomalously low and is most likely due to errors introduced because of heavy oxidation of the hottest span, and relatively large extraneous heat flows for which the computerized analysis could not completely compensate; it subsequently causes an anomalously large decreasing trend of the fitted curve with increasing temperature, particularly in the range of about 825 to 925 K.

The fitted curves for λ and ρ each tend to cluster into two groups, one with λ (ρ) near that of oxygen-free copper and the other with λ (ρ) somewhat lower (higher). The reason for this separation is not known. However, other measured data for both properties indicate such variation is not unreasonable for dilute copper alloys [3]. In addition, a consistency check was made by calculating the Lorenz function for each specimen from the smoothed data at even temperature intervals. Over the whole range of the data, the Lorenz function was almost temperature independent and close to the theoretical Lorenz number for all specimens except R14. Although the Lorenz functions are not presented, comparison

between measured and predicted values for λ using the Smith-Palmer equation are given in Table 6. The same conclusion about the consistency of the results is obtained. It is thus felt that the clustering of the curves into two groups is coincidental and has no other significance.

The results for specimen R14 are an exception to the above conclusion. In addition to an anomalously low calculated Lorenz function (compared to the other specimens) and a significant lack of agreement with predictions of the Smith-Palmer equation, there is also a large scatter in the electrical resistivity data (Fig. 2). Either the results for λ or ρ, or both, must be anomalous. Fictitious electrical resistivity values calculated from the Smith-Palmer relation using measured values of λ closely approximated a linear function of temperature with only a small amount of data scatter (about 2% standard deviation) and a fitted straight line closely matches the results of the measured ρ data of the other specimens both in slope and in magnitude. These facts lead to the belief that the λ results for R14 are probably valid, and thus that the ρ results for R14 are probably mostly anomalous (although there was close agreement between the fictitious calculated ρ values and most of the actual measured ρ data points in the temperature range 373-573 K).

The accuracy of the smoothed values of λ obtained with this apparatus was established from a comparison of results on round-robin specimens by NBS and other laboratories. It is estimated to be about $\pm$ 2 to 3 percent [5-8]. Because of the use of thermocouples as potential taps in the measurement of ρ, similar uncertainties exist in geometry and thermoelectric effects. Since these are the dominant sources of error, it is estimated that the accuracy of the smoothed values of ρ are about

the same as that for λ.

4. Conclusion

Measured values of the thermal conductivity and electrical resistivity of oxygen-free copper and six copper-base alloys are presented. With one exception, the measured λ values of these materials and the λ values predicted by the Smith-Palmer equation using measured ρ values agree to within about 3 percent. The exceptional case is believed to be due to erroneous ρ data, and not due to limits of validity of the Smith-Palmer equation.

5. Acknowledgment

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Figure Captions

Figure 1 Thermal Conductivity of Oxygen Free Copper and Six Copper-Base Alloys

Figure 2 Electrical Resistivity of Oxygen Free Copper and Six Copper-Base Alloys

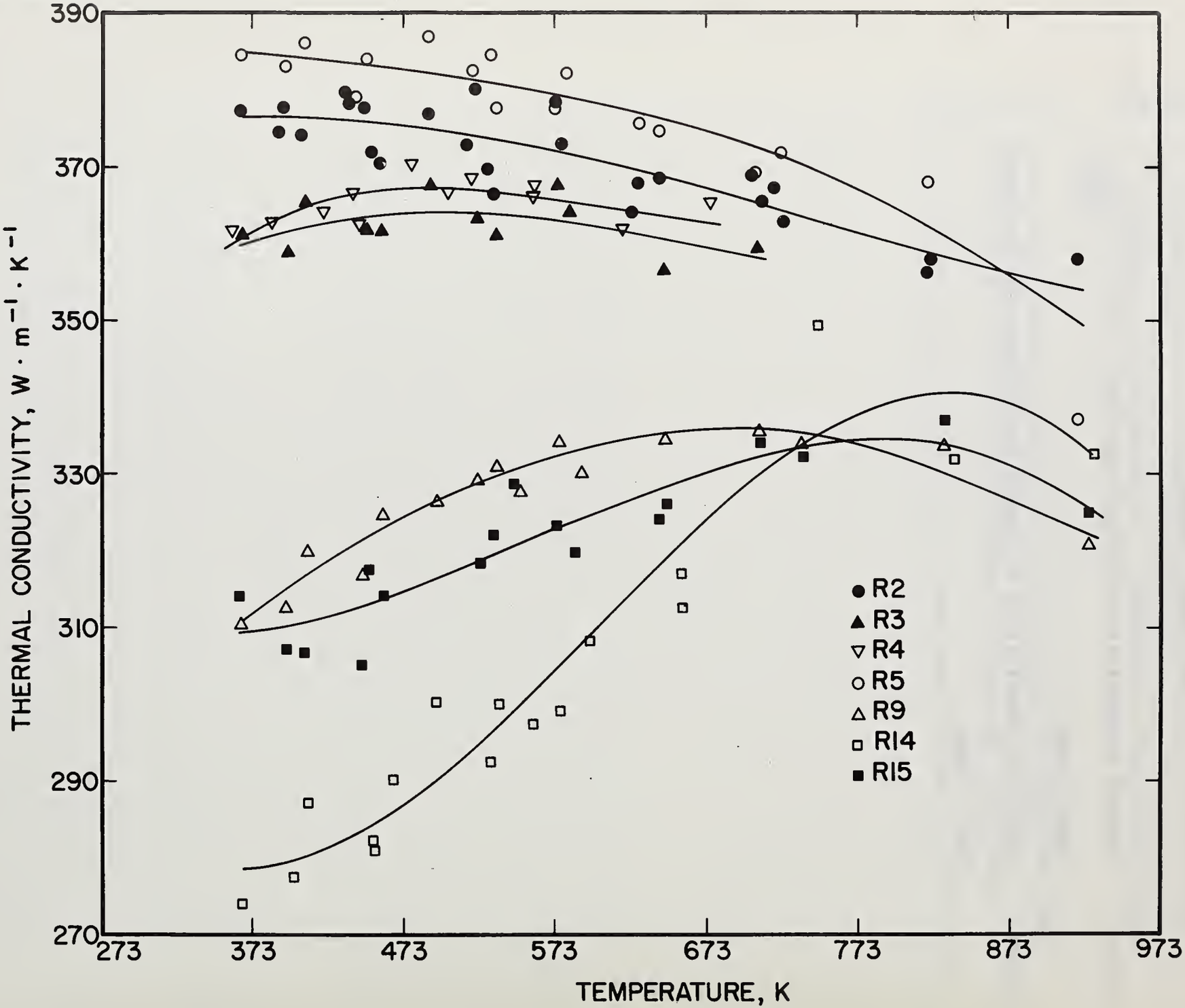

Figure 1 Thermal Conductivity of Oxygen Free Copper and Six Copper-Base Alloys

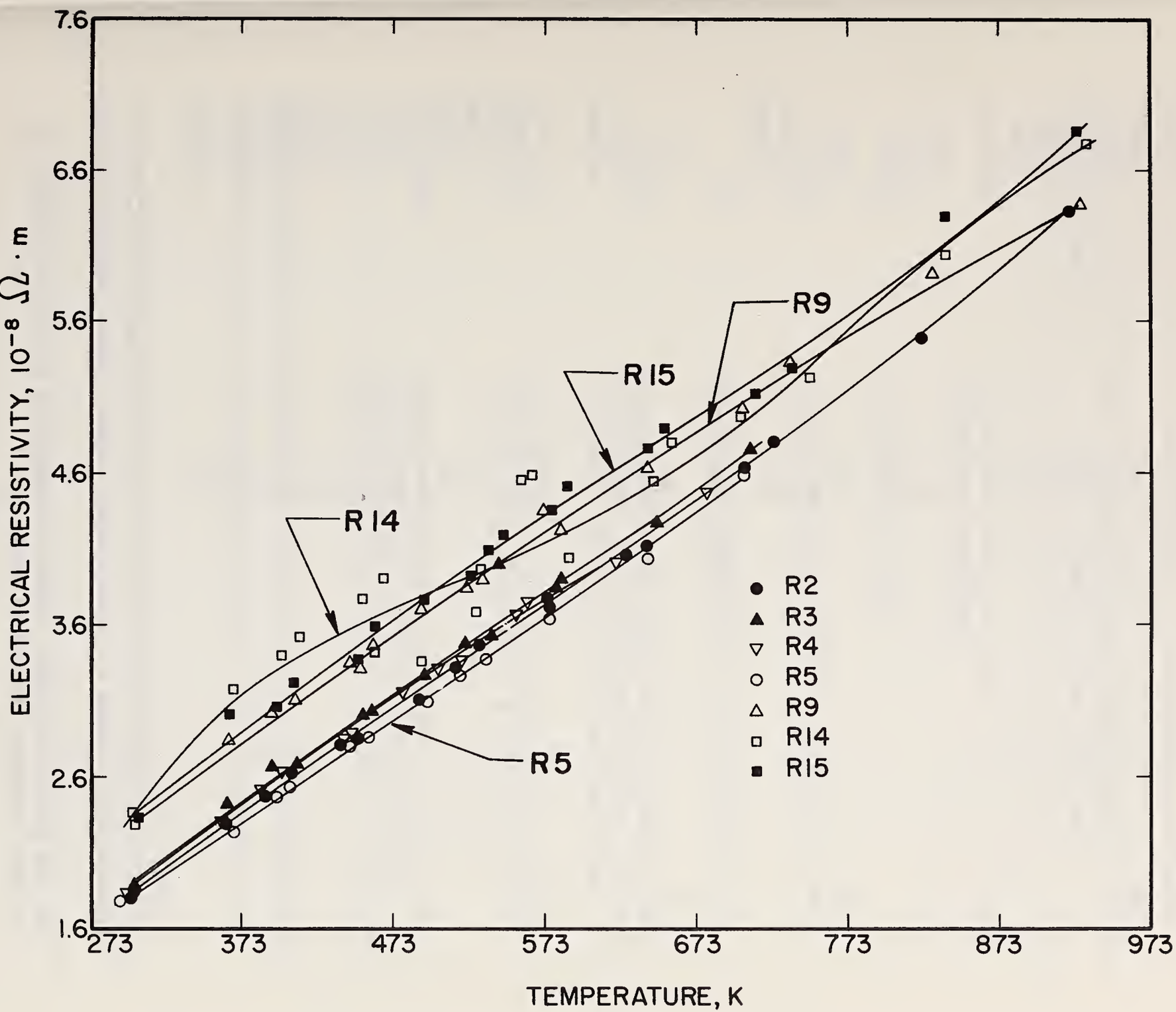

Figure 2 Electrical Resistivity of Oxygen Free Copper and Six Copper-Base Alloys

Table 1a Chemical Composition of the Copper Samples*

Identification Number	Chemical Composition	Percent Weight
R2	Pb	0.000
	Sn	0.000
	Zn	0.00
	Fe	0.002
	Ni	0.002
	Zr	0.20
	Cu	Balance
R3	P	0.005
	Te	0.51
	Cu	99.50
R4	Mg	0.00
	Si	0.02
	Cr	1.07/1.13
	Cu	Balance
R5+	Oxygen Free Copper	-
R9	Mg	0.05
	Zr	0.17
	Cr	0.48
	Cu	Balance
R14	Pb, Sn	1 ppm
	Bi	<0.0001
	Be	<0.0002
	Si	<0.0001
	Ca	<0.0003
	Mn	<0.0003
	Co	<0.001
	Ni	<0.001
	Zn	<0.001
	As	<0.002
	P	<0.002
	Sb	<0.002
	Zr	0.49
	Ag	2.74
	Cu	Balance
R15**		

* Information provided by Lewis Research Center, NASA, Cleveland, Ohio.

** R15 was made to the same chemical composition as R14 but differs in its heat treatment (shown in Table 1b).

+ Chemical composition not supplied by NASA.

Table 1b Thermal History of the Copper Samples*

Identification No.	History of Heat Treatment
R2	Extruded at 1233 K and aged at 693 K in cracked natural gas atmosphere
R3	Not provided by NASA
R4	Solution annealed at 1273 K, quenched and aged at 773 K for 3 hours
R5	Hot rolled at 1051-1109 K and cold drawn
R9	Solution heat treated at 1331 K in neutral (barium chloride) salt, quenched in water, cold drawn and aged at 773 K for 2 1/2 hours and drawn
R14	Centrifugally cast, hot forged at 940 to 1134 K, solution treated at 1451 ± 8 K for 2 hours
R15	Conventionally cast, hot rolled at 1134 ± 8 K, solution annealed at 1451 ± 8 K for 1 hour, quenched in water, aged at 773 K for 3 hours and air cooled

*Information provided by Lewis Research Center, NASA, Cleveland, Ohio.

Table 2 Mechanical Properties of the Copper Samples*

Alloy	T (K)	Strength (MN/m^2) Yield	Tensile**	Reduction in Area (%)
R2	297	336	378	81.5
	811	213	216	84
R3	297	355	360	37.5
	811	24.8	74.2	28
R4	297	521	529	56.5
	811	255	262	17.5
R5	297	309	317	82
	811	23.5	70.3	65
R9	297	537	550	77
	811	296	309	40.5
R14	297	82.4	295.1	53.8
	811	63.4	125.5	61.5
R15	297	99.0	288.5	55
	811	85.1	127.0	53.5

* Information provided by Lewis Research Center, NASA, Cleveland, Ohio

** Tensile strain rate: 2×10^{-3} sec^{-1} in all tests

Table 3 Values of the Coefficients of the Least Squares Fit Cubic Equations*

Coefficient	R2**	R3	R4	R5	R9	R14	R15
α_0	386.0	349.8	342.1	392.0	294.4	286.0	310.9
α_1	-1.061×10^{-2}	1.421	0.2821	-0.9031×10^{-1}	1.946×10^{-1}	-1.761×10^{-1}	-5.545×10^{-2}
α_2	-2.941×10^{-6}	-4.203×10^{-3}	-0.9871×10^{-3}	3.022×10^{-4}	-2.147×10^{-4}	1.147×10^{-3}	4.837×10^{-4}
α_3	-1.047×10^{-7}	3.175×10^{-6}	1.040×10^{-5}	-4.469×10^{-7}	-3.142×10^{-8}	-1.175×10^{-6}	-5.577×10^{-7}
β_0	1.631×10^{-8}	1.656×10^{-8}	1.667×10^{-8}	1.533×10^{-8}	2.111×10^{-8}	2.159×10^{-8}	2.075×10^{-8}
β_1	7.572×10^{-11}	8.677×10^{-11}	8.124×10^{-11}	8.390×10^{-11}	7.134×10^{-11}	1.035×10^{-10}	9.071×10^{-11}
β_2	3.267×10^{-14}	-8.661×10^{-14}	-5.945×10^{-14}	-8.760×10^{-14}	-2.214×10^{-15}	-1.722×10^{-13}	-7.821×10^{-14}
β_3	4.315×10^{-17}	1.169×10^{-16}	7.187×10^{-16}	1.298×10^{-16}	-1.017×10^{-17}	1.885×10^{-16}	7.860×10^{-17}

* Appropriate temperature ranges of applicability are given in Figures 1 and 2

** See Table 1 for chemical composition

Table 4 Smoothed Values of the Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$) of Oxygen Free Copper and Six Copper-Base Alloys

T (K)	R2	R3	R4	R5	R9	R14	R15
373	376	360	361	385	312	279	310
423	376	363	366	384	319	281	311
473	375	364	367	383	324	287	315
523	373	364	367	382	329	295	319
573	372	363	366	380	333	305	323
623	370	362	364	377	335	314	327
673	367	360	364	375	336	324	330
723	364	-	-	371	336	332	333
773	361	-	-	367	334	338	334
823	359	-	-	362	331	341	334
873	356	-	-	356	327	339	331
923	354	-	-	349	321	333	326

Table 5 Smoothed Values of the Electrical Resistivity ($10^{-8}\Omega \cdot m$) of Oxygen-Free Copper and Six Copper-Base Alloys

T (K)	R2	R3	R4	R5	R9	R14	R15
323	2.00	2.07	2.06	1.93	2.47	2.63	2.51
373	2.36	2.45	2.43	2.30	2.82	3.04	2.91
423	2.71	2.80	2.78	2.64	3.17	3.39	3.28
473	3.05	3.14	3.11	2.96	3.52	3.69	3.64
523	3.39	3.47	3.44	3.29	3.86	3.96	3.98
573	3.72	3.79	3.76	3.61	4.20	4.22	4.30
623	4.07	4.13	4.09	3.97	4.54	4.48	4.63
673	4.41	4.49	4.42	4.32	4.86	4.75	4.95
723	4.77	-	-	4.71	5.18	5.05	5.29
773	5.14	-	-	-	5.50	5.39	5.63
823	5.52	-	-	-	5.80	5.78	6.00
873	5.93	-	-	-	6.09	6.24	6.40
923	6.36	-	-	-	6.37	6.79	6.82

Table 6 Thermal Conductivity Values Computed Using the Smith-Palmer Equation, λ ($W\ m^{-1}\ K^{-1}$) and Comparison[+] With Smoothed Values, λ_m ($W \cdot m^{-1} \cdot K^{-1}$)

	R2		R3		R4		R5		R9		R14		R15	
T(K)	λ	Dif[+]	λ	Dif	λ	Dif	λ	Dif	λ	Dif	λ	Dif	λ	Dif
373	385	-2.2	371	-3.0	374	-3.6	395	-2.6	324	-3.8	300	-7.5	313	-1.0
423	380	-1.1	369	-1.6	371	-1.4	390	-1.6	326	-2.2	305	-8.5	316	-1.6
473	378	-0.8	367	-0.8	371	-1.4	389	-1.6	329	-1.5	314	-9.4	318	-0.9
523	376	-0.8	368	-1.1	371	-1.4	387	-1.3	331	-0.6	323	-9.5	322	-0.9
573	376	-1.0	369	-1.6	372	-1.6	387	-1.8	334	-0.3	332	-8.8	326	-0.9
623	373	-0.8	368	-1.7	371	-1.9	382	-1.9	335	-1.5	340	-8.3	329	-0.6
673	372	-1.4	366	-1.7	371	-1.9	380	-1.3	338	-0.6	346	-6.8	332	-0.6
723	370	-1.6	-	-	-	-	374	-1.9	341	-1.5	350	-5.4	334	-0.3
773	370	-2.5	-	-	-	-	-	-	343	-3.0	350	-3.5	336	-0.6
823	364	-1.4	-	-	-	-	-	-	347	-4.8	348	-2.0	335	-0.3
873	359	-0.8	-	-	-	-	-	-	350	-7.0	342	-0.8	333	-0.6
923	354	0	-	-	-	-	-	-	354	-10.3	332	0.3	331	-1.5

[+] Difference = $\frac{\lambda_m - \lambda}{\lambda_m} \times 100\%$

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Measurements of the thermal conductivity, λ, and electrical resistivity, ρ, of oxygen free copper and six copper-base alloys in the temperature range 298 to 924 K are presented. Except for copper, the λ and ρ values of copper alloys having the same chemical composition as those given in this paper have not been previously reported. The measured values of λ ($W \cdot m^{-1} \cdot K^{-1}$) and ρ ($\Omega \cdot m$) were found to conform, within 10 percent, to the predictions of the Smith-Palmer equation, $\lambda = 2.39 \times 10^{-8} T/\rho + 7.50$ $[W \cdot m^{-1} \cdot K^{-1}]$, where T is the thermodynamic temperature expressed in kelvins.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Copper-base alloy properties; electrical resistivity; Smith-Palmer equation; thermal conductivity

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